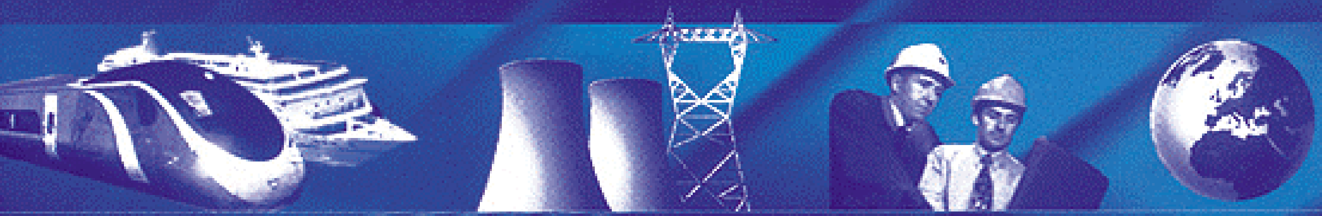

# Advanced SCR Control for Dynamic Ammonia Distribution

Conference on Selective Catalytic Reduction and Non-Catalytic Reduction for NOx Control

Pittsburgh, PA

October 30, 2003

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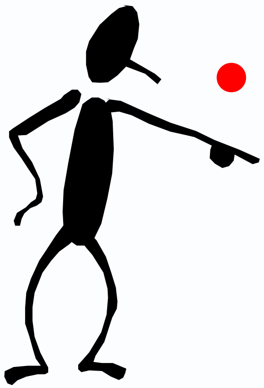
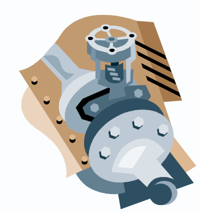
# Key Performance Indicators for the SCR



- Key Performance Indicators:
  - NOx removal efficiency,
  - Ammonia slip,
  - Ammonia utilization efficiency

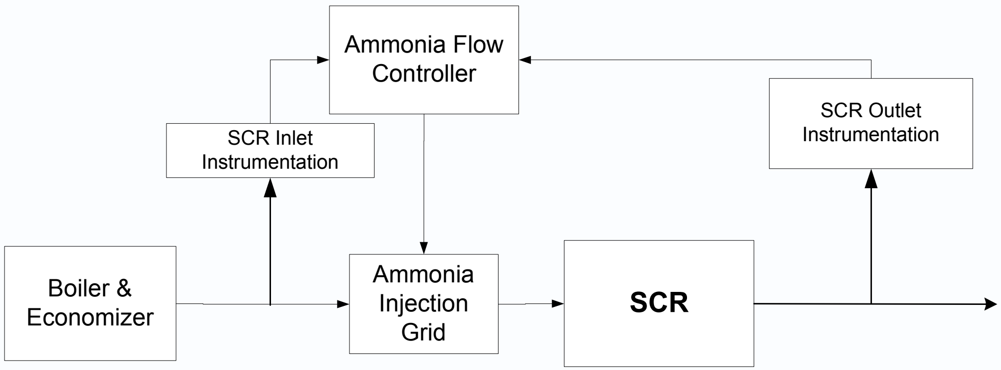
- Impact of Operational Factors
  - Maldistribution of Inlet NOx
  - Process/profile noise (within design tolerances)

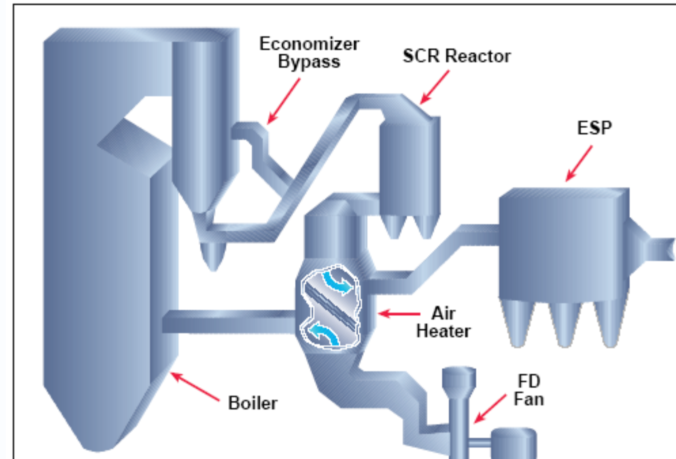
- Impact of the process control system
  - Typical SCR process control system
  - Advanced process control system



# The SCR Process

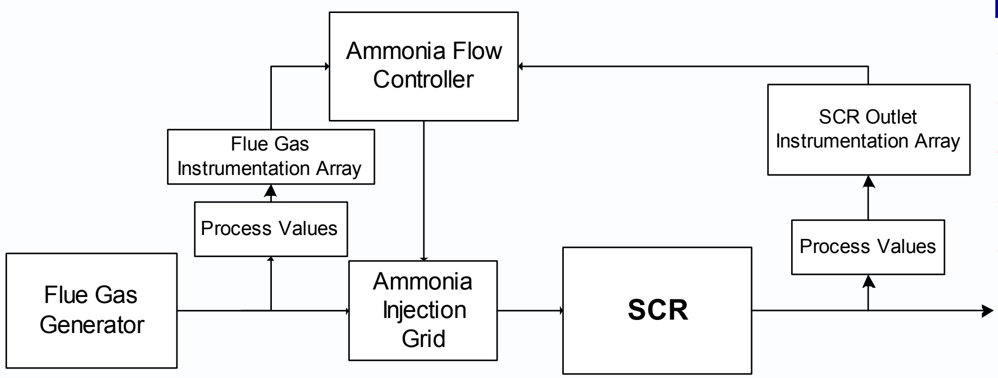
## SCR in the field



Schematic flow diagram of SCR process

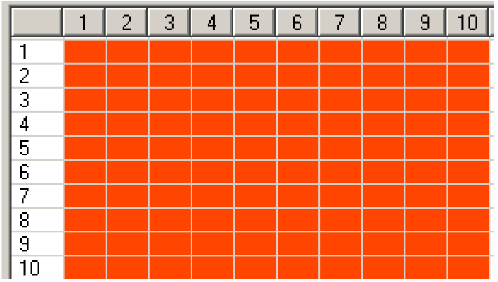
## Simulation "process" (blocks)




Benefits of using a Simulator:
- Controlled, repeatable conditions
- Unlimited "instrumentation"
- Simple re-configuration
- No impact on production/performance
- Faster execution than "real-process"

# Dynamic Simulator

- SCR Reaction:
  - First principle steady-state model
  - Kinetic equation reference: Control of Nitrogen Oxide Emission: Selective Catalytic Reduction, Clean Coal Technology, Topical Report #9, US DOE, July 1997
- Process Dynamics:
  - First-order exponential filter
  - Pure dead-time/delay blocks
  - Instrumentation lag included!
- Reactor "Squares"
  - 10x10 grid – 100 squares
  - Each square modeled as an independent reactor
- Execution frequency: One "Real" second



# Flue Gas “Generator”

- NOx Inlet:  Bulk Value & Distribution Profile
  - Base NOx load – combustion conditions,
  - Plant load,
  - Fuel/air ratio,
  - Process noise,
  - Maldistribution:  Burner operation, duct work, etc.

- Flue gas velocity:  Bulk Value

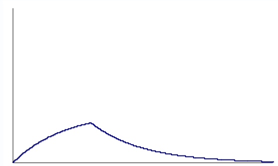
- Flue gas water content:  Bulk Value (fixed:  10%)

# Inlet NOx:  Factors

- Base NOx load:  400 ppm
- Plant Load:

$$NOx\,offset = \left(\frac{100.0 - load_{current}}{100.0}\right) * 1.25$$

- Fuel/air ratio (dynamic):



- Random Process noise:
  - Uniform distribution
  - Scaled based on load
  - Applied to:
    - Base inlet NOx
    - Each simulation square
- Maldistribution

# Inlet NOx: Maldistribution

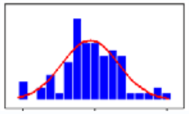
## Goal: Simulate NOx load profile:

- Correlated, but random movement

  "Spring" for each simulation square

  - Energy: Gaussian noise

$$noise = \frac{\sum_{n=1}^{10} rnd()}{10} \qquad process\_noise = range * (noise - 0.5)$$

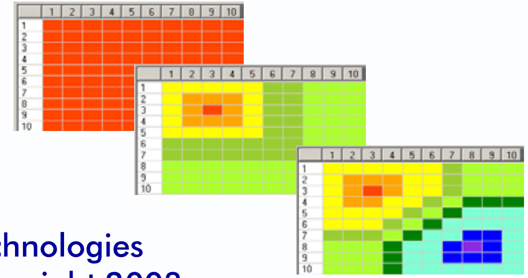


  - Correlation: algebraic relationship to other "squares"

$$InletNOx_{(x,y)} = \sum_{i=1,j=1}^{10,10} filtered\_process\_noise_{(i,j)} * \left(\chi_{(i,j)}\right)^3$$

$$\chi_{i,j} = \frac{10 - \max(abs(x-i), abs(y-j))}{10}$$

- Fixed overlay
  - Base: No offset (prefect distribution)
  - Profiles: Fixed peak and/or dip



# Instrumentation

- Flow: Fast: essentially no lag
- Composition analyzers:
  - 4 “Sample” points – limited information
  - Pure dead-time:
    - Sample system transport lag
    - Analyzer cycle time
  - “Best-case”: Approximately 25 – 30 second lag
  - Two sets of “books” in the simulator:
    - Process values
    - Instrumentation values (used by the control system)

# Ammonia Injection Grid

- “Best-case”:
  - Perfect tuning of grid so that NOx:NH3 ratio is the same at every point
    - Uniform NOx distribution (no offsets), and
    - Uniform ammonia distribution
  - Simulation:  All offsets are zero…
- Ammonia flow controller assumed to be perfect (process value = setpoint) – with some relatively fast dynamics.

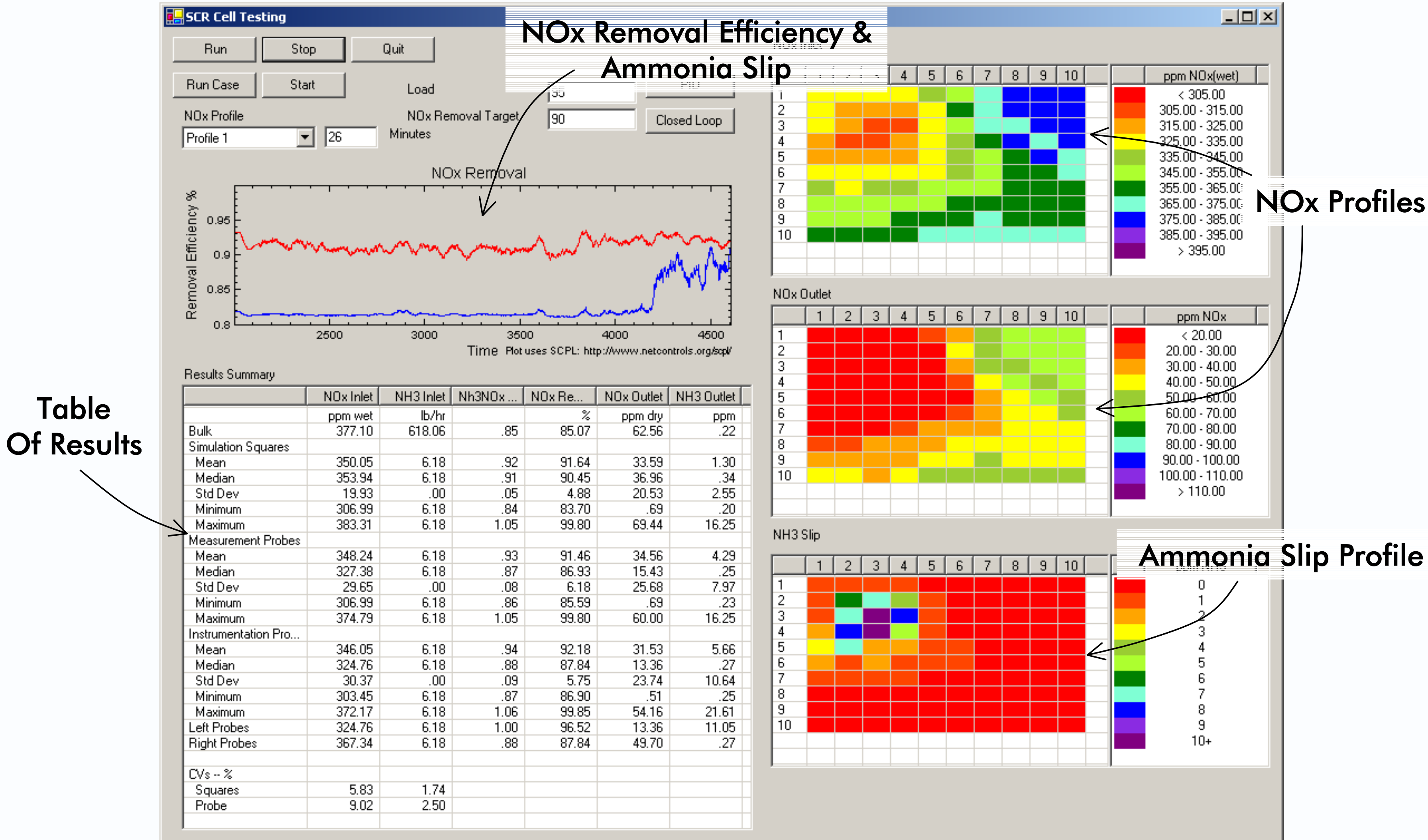
# Simulator Block: SCR

- 100 reaction squares – modeled independently
- Results (summarized):
  - Simulation Squares: Summary
    - Process Values (live)
    - Measurement Probes (delayed)
  - Instrumentation (from Measurement Probes)
    - 4-point overall summary
    - Left & Right sides

Results Summary

| | NOx Inlet | NH3 Inlet | Nh3NOx ... | NOx Re... | NOx Outlet | NH3 Outlet |
|---|---|---|---|---|---|---|
| | ppm wet | lb/hr | | % | ppm dry | ppm |
| Bulk | 365.18 | 626.72 | .91 | 91.21 | 35.67 | .31 |
| Simulation Squares | | | | | | |
| Mean | 354.34 | 6.27 | .94 | 93.97 | 23.78 | .47 |
| Median | 354.78 | 6.27 | .94 | 93.67 | 24.25 | .43 |
| Std Dev | 4.53 | .00 | .01 | 1.18 | 4.94 | .10 |
| Minimum | 344.70 | 6.27 | .91 | 91.41 | 13.38 | .32 |
| Maximum | 364.36 | 6.27 | .97 | 96.51 | 34.76 | .78 |
| Measurement Probes | | | | | | |
| Mean | 353.10 | 6.27 | .94 | 94.29 | 22.42 | .48 |
| Median | 350.92 | 6.27 | .94 | 93.72 | 20.05 | .44 |
| Std Dev | 2.83 | .00 | .01 | .74 | 3.08 | .06 |
| Minimum | 350.52 | 6.27 | .93 | 93.33 | 19.61 | .41 |
| Maximum | 356.81 | 6.27 | .95 | 94.97 | 26.46 | .54 |
| Instrumentation Pro... | | | | | | |
| Mean | 353.59 | 6.27 | .94 | 93.46 | 25.71 | .43 |
| Median | 351.10 | 6.27 | .93 | 92.80 | 22.95 | .38 |
| Std Dev | 3.14 | .00 | .01 | .87 | 3.63 | .06 |
| Minimum | 350.50 | 6.27 | .93 | 92.46 | 21.45 | .37 |
| Maximum | 357.49 | 6.27 | .95 | 94.49 | 29.97 | .50 |
| Left Probes | 353.99 | 6.27 | .94 | 93.47 | 25.71 | .43 |
| Right Probes | 353.19 | 6.27 | .94 | 93.45 | 25.71 | .42 |

# Simulator Interface




| | NOx Inlet | NH3 Inlet | Nh3NOx ... | NOx Re... | NOx Outlet | NH3 Outlet |
|---|---|---|---|---|---|---|
| | ppm wet | lb/hr | | % | ppm dry | ppm |
| Bulk | 377.10 | 618.06 | .85 | 85.07 | 62.56 | .22 |
| Simulation Squares | | | | | | |
| Mean | 350.05 | 6.18 | .92 | 91.64 | 33.59 | 1.30 |
| Median | 353.94 | 6.18 | .91 | 90.45 | 36.96 | .34 |
| Std Dev | 19.93 | .00 | .05 | 4.88 | 20.53 | 2.55 |
| Minimum | 306.99 | 6.18 | .84 | 83.70 | .69 | .20 |
| Maximum | 383.31 | 6.18 | 1.05 | 99.80 | 69.44 | 16.25 |
| Measurement Probes | | | | | | |
| Mean | 348.24 | 6.18 | .93 | 91.46 | 34.56 | 4.29 |
| Median | 327.38 | 6.18 | .87 | 86.93 | 15.43 | .25 |
| Std Dev | 29.65 | .00 | .08 | 6.18 | 25.68 | 7.97 |
| Minimum | 306.99 | 6.18 | .86 | 85.59 | .69 | .23 |
| Maximum | 374.79 | 6.18 | 1.05 | 99.80 | 60.00 | 16.25 |
| Instrumentation Pro... | | | | | | |
| Mean | 346.05 | 6.18 | .94 | 92.18 | 31.53 | 5.66 |
| Median | 324.76 | 6.18 | .88 | 87.84 | 13.36 | .27 |
| Std Dev | 30.37 | .00 | .09 | 5.75 | 23.74 | 10.64 |
| Minimum | 303.45 | 6.18 | .87 | 86.90 | .51 | .25 |
| Maximum | 372.17 | 6.18 | 1.06 | 99.85 | 54.16 | 21.61 |
| Left Probes | 324.76 | 6.18 | 1.00 | 96.52 | 13.36 | 11.05 |
| Right Probes | 367.34 | 6.18 | .88 | 87.84 | 49.70 | .27 |
| CVs -- % | | | | | | |
| Squares | 5.83 | 1.74 | | | | |
| Probe | 9.02 | 2.50 | | | | |

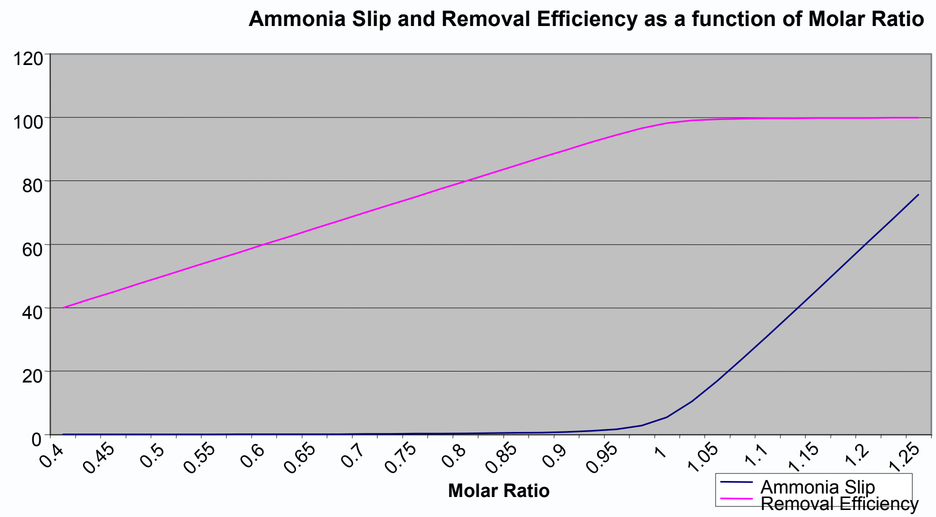
# Observation: Ammonia Slip

- “Bulk” FALSELY shows “better” performance than Simulation squares

Results Summary

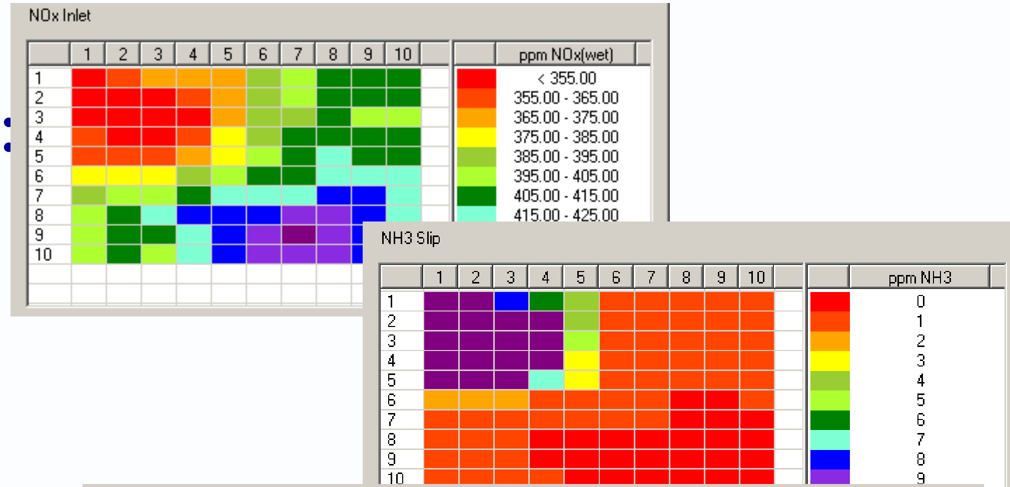
| | NOx Inlet | NH3 Inlet | Nh3NOx ... | NOx Re... | NOx Outlet | NH3 Outlet |
|---|---|---|---|---|---|---|
| | ppm wet | lb/hr | | % | ppm dry | ppm |
| Bulk | 400.00 | 728.72 | .90 | 89.96 | 44.61 | .57 |
| Simulation Squares | | | | | | |
| Mean | 399.02 | 7.29 | .90 | 90.27 | 43.62 | .68 |
| Median | 398.77 | 7.29 | .90 | 90.07 | 43.26 | .58 |
| Std Dev | 14.31 | .00 | .03 | 3.19 | 15.63 | .29 |
| Minimum | 372.45 | 7.29 | .85 | 84.45 | 15.01 | .37 |
| Maximum | 426.34 | 7.29 | .97 | 96.37 | 73.68 | 1.58 |

- Slip is NON-LINEAR!
  - Increased sensitivity as NH3:NOx ratio increases…



# Observation: Observed KPIs are a strong function of instrumentation

- Left upper quadrant:
  - Low inlet NOx
  - High ammonia slip
- Right lower quadrant:
  - High inlet NOx
  - Low ammonia slip
- However REASONABLE
  - Bulk conditions,
  - Average




Results Summary

| | NOx Inlet | NH3 Inlet | Nh3NOx ... | NOx Re... | NOx Outlet | NH3 Outlet |
|---|---|---|---|---|---|---|
| | ppm wet | lb/hr | | % | ppm dry | ppm |
| Bulk | 400.00 | 751.63 | .93 | 92.74 | 32.27 | .82 |
| Simulation Squares | | | | | | |
| Mean | 399.93 | 7.52 | .93 | 92.20 | 36.24 | 4.87 |
| Median | 406.03 | 7.52 | .91 | 91.22 | 38.83 | .68 |
| Std Dev | 28.57 | .00 | .07 | 5.12 | 24.83 | 9.39 |
| Minimum | 331.33 | 7.52 | .83 | 83.21 | .48 | .35 |
| Maximum | 446.34 | 7.52 | 1.12 | 99.87 | 83.29 | 45.33 |
| Measurement Probes | | | | | | |
| Mean | 399.13 | 7.52 | .94 | [illegible] | [illegible] | 11.73 |
| Median | 368.50 | 7.52 | .87 | [illegible] | [illegible] | .45 |
| Std Dev | 47.57 | .00 | .12 | 6.61 | 32.27 | 22.40 |
| Minimum | 331.33 | 7.52 | .84 | 84.12 | .48 | .37 |
| Maximum | 441.44 | 7.52 | 1.12 | 99.87 | [illegible] | [illegible] |
| Instrumentation Pro... | | | | | | |
| Mean | 391.31 | 7.52 | .96 | 92.61 | 34.33 | 13.93 |
| Median | 359.61 | 7.52 | .88 | 88.33 | 13.58 | .52 |
| Std Dev | 47.87 | .00 | .13 | 5.72 | 27.48 | 26.53 |
| Minimum | 323.26 | 7.52 | .87 | 86.50 | .40 | .44 |
| Maximum | 433.34 | 7.52 | 1.15 | 99.89 | 64.99 | 53.72 |
| Left Probes | 367.96 | 7.52 | 1.03 | 95.02 | 22.78 | 27.16 |
| Right Probes | 414.65 | 7.52 | .90 | 90.21 | 45.88 | .71 |

Full Range

Left/Right

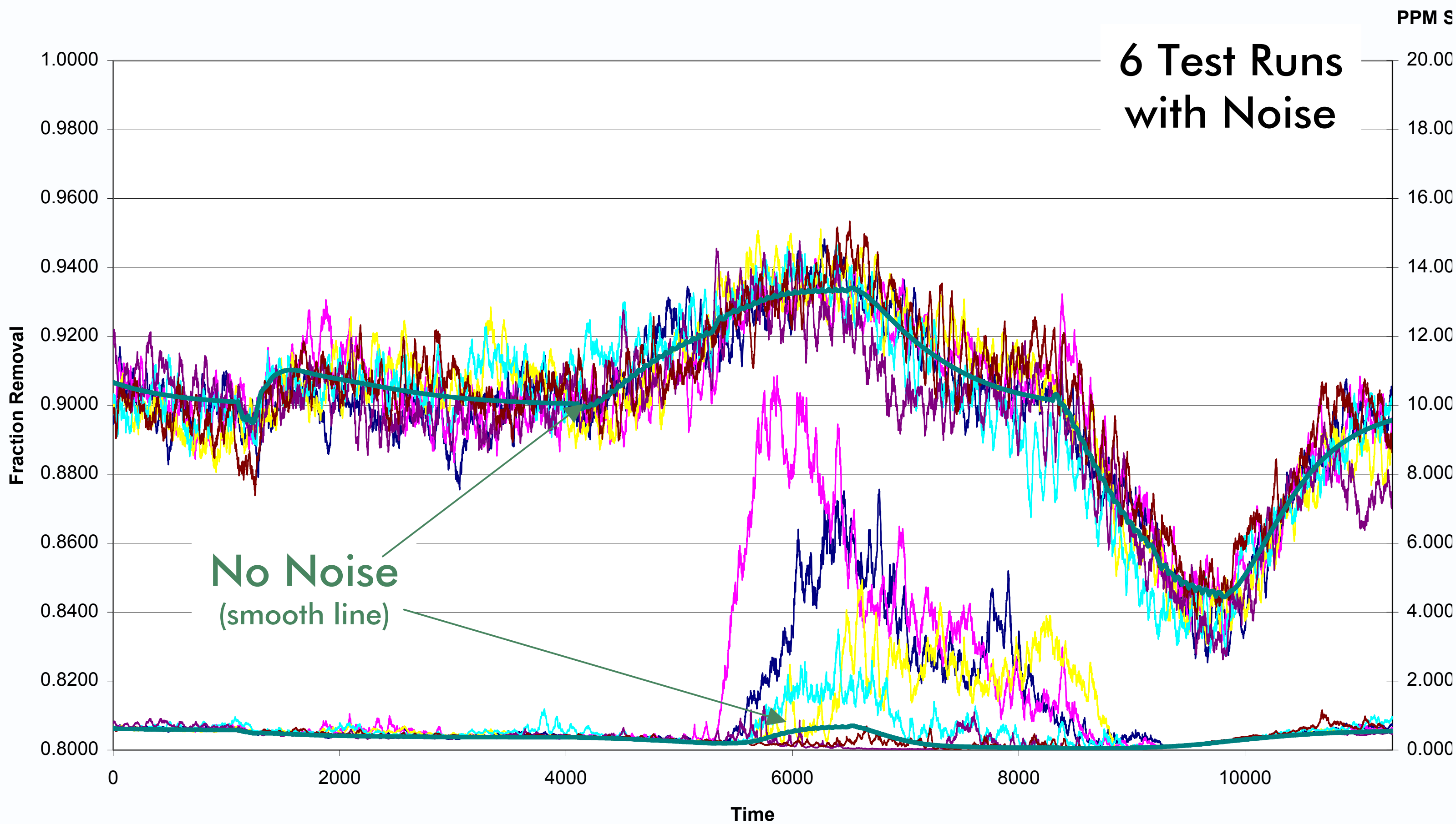
# Control Performance Tests

- Series of test "runs" under controlled conditions
  - Same starting conditions
    - SCR configuration, model, and reaction constants
    - Dynamic elements
    - Fixed NOx inlet profile and noise ranges
  - Same profile of operating changes
    - Load changes
    - Fixed NOx inlet profile changes
- Process Control Systems:
  - Objectives:
    - NOx Removal Efficiency 90+%
    - Ammonia slip: Target at 2 ppm, hard constraint at 5 ppm
  - Control configurations:
    - PID – typical SCR process control system
    - Multivariable control: single adjustable ammonia flow
    - Multivariable control: two adjustable ammonia flows

# Performance Test: Run Profile

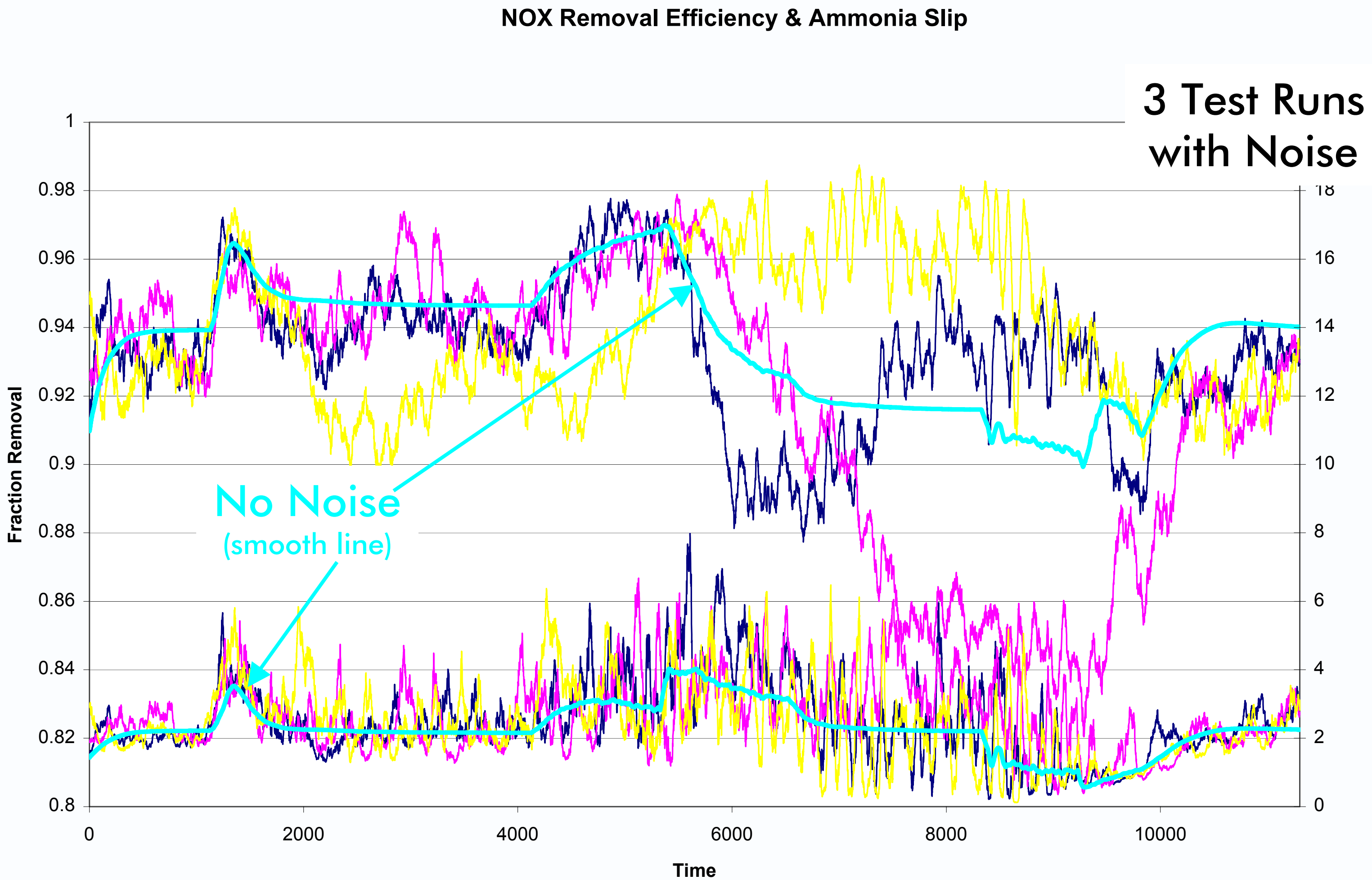
| Time (minutes) into Run | Operating Action |
|---|---|
| 0 | Start of Run |
| 10 | Ramp load down at 2%/minute |
| 11.5 | Change to NOx Inlet Profile 1 |
| 12.5 | Stop load ramp (95%) |
| 60 | Ramp load down at 0.5%/minute |
| 80 | Change to NOx Inlet Profile 2 |
| 100 | Stop load ramp (75%) |
| 130 | Ramp load up at 1%/minute |
| 145 | Change to NOx Inlet Profile 1 |
| 155 | Stop load ramp (100%) |
| 155 | Change to NOx Inlet Profile 0 |
| 180 | End of Run |

# PID Control



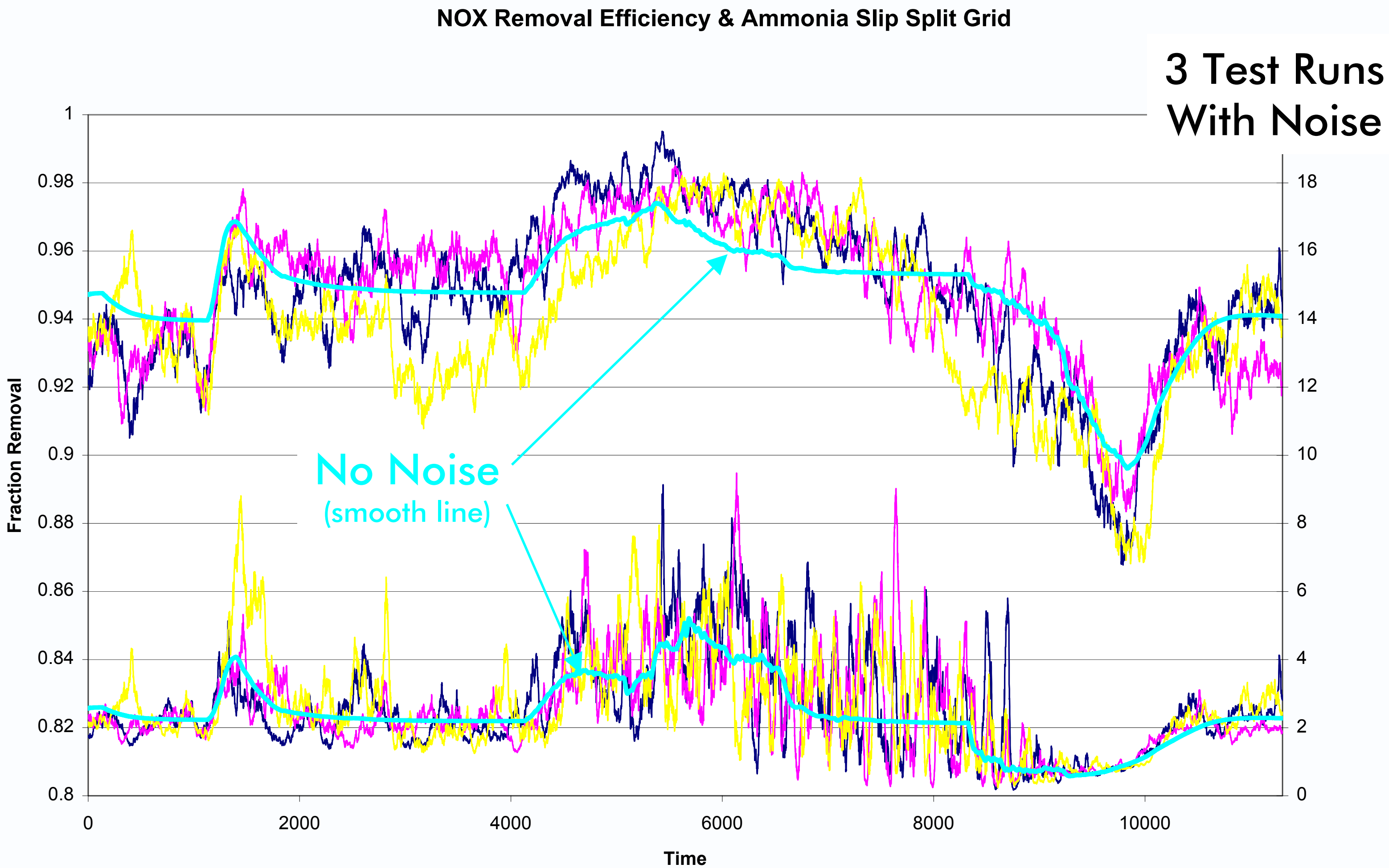

- "Adequate" control of NOx Removal Efficiency: Impacted by:
  - Disturbances (load changes & process noise)
  - Instrumentation delays
- No Ammonia slip control

# MPC – fixed ammonia grid




- Increased NOx Removal Efficiency
- Control of Ammonia slip

# MPC – split ammonia grid



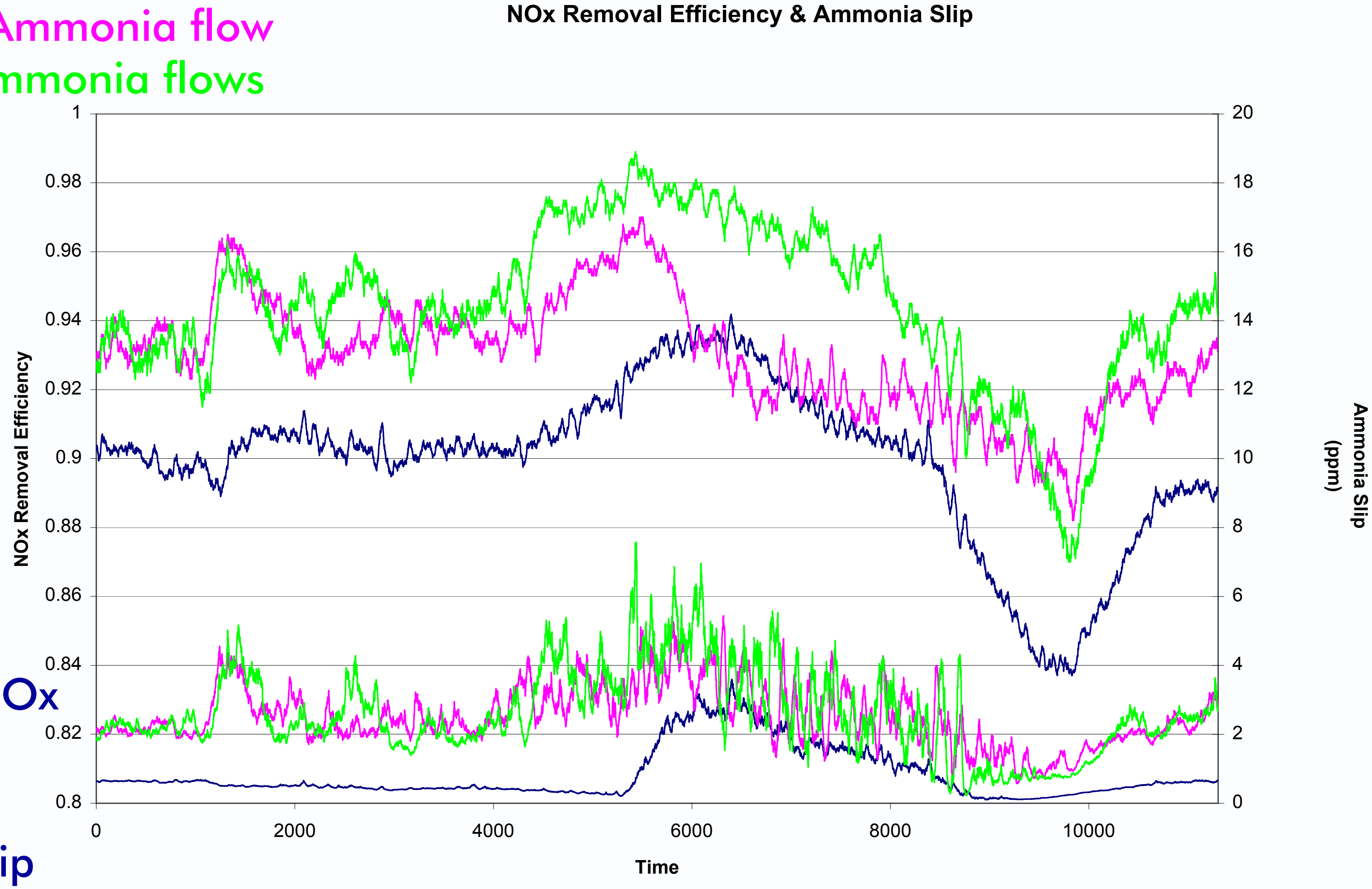

- Even more NOx Removal
- Better control of Ammonia slip

# Control Comparison

PID

MPC – Single Ammonia flow

MPC – Dual Ammonia flows




MPC yields:

- Increased NOx removal efficiency
- Ammonia slip control

# Control Test Summary

- MPC:
  - Increased NOx Removal
  - Ammonia Slip Control
- Dual Ammonia flows:
  - Additional NOx Removal
  - More balanced slip control

| | PID Fixed Grid w/ Noise | MPC Fixed Grid w/ Noise | MPC Dual Grid w/ Noise |
|---|---|---|---|
| **Simulation Squares** | | | |
| NOx Removal Efficiency % (mean) | 89.95 | 93.15 | 94.55 |
| NOx Removal Efficiency % (std dev) | 3.86 | 2.74 | 2.23 |
| Ammonia slip ppm (mean) | 0.8220 | 1.9779 | 2.9588 |
| Ammonia slip ppm (std dev) | 1.2558 | 1.0052 | 1.7657 |
| Total Ammonia used (lb) | 1855.05 | 1916.33 | 2002.33 |
| Total NOx removed (lb) | 5006.82 | 5156.67 | 5376.33 |
| **Instrumentation Probes** | | | |
| NOx Removal Efficiency % (mean) | 89.99 | 92.99 | 94.52 |
| NOx Removal Efficiency % (std dev) | 4.79 | 2.75 | 2.31 |
| Ammonia slip ppm (mean) | 1.4860 | 2.5191 | 2.5740 |
| Ammonia slip ppm (std dev) | 2.4682 | 1.1008 | 1.3855 |
| **Left Probes** | | | |
| NOx Removal Efficiency % (mean) | 88.16 | 91.34 | 94.57 |
| Ammonia slip ppm (mean) | 0.3079 | 1.7614 | 2.3994 |
| **Right Probes** | | | |
| NOx Removal Efficiency % (mean) | 91.83 | 94.66 | 94.48 |
| Ammonia slip ppm (mean) | 2.6641 | 3.2762 | 2.6905 |

# Conclusions: Impact on KPIs:

- Process Challenges:
  - Maldistribution of inlet NOx
  - Process Noise
- Improvements:
  - Additional analyzers and control valves
  - Advanced Process Control techniques:
    - Increase flexibility
    - Improve performance
      - Increased NOx removal,
      - Controlled ammonia slip

# Acknowledgements

- Thank You:
  - Dr. Karlene Hoo, Texas Tech University, Chemical Engineering

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